Technical Note 3-88

# USE OF COLOR CRTS IN AIRCRAFT COCKPITS: A LITERATURE SEARCH

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Essex Corporation

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A literature search was conducted to assess the utility and feasibility of incorporating color cathode ray tubes (CRTs) in military aircraft cockpits and is presented in annotated bibliography format. The advantages and disadvantages of color CRTs are reviewed. It is concluded that the incorporation of color on aircraft CRTs will prove beneficial and that potential problems associated with the use of color displays can be eliminated with proper display design and the advancement of technology.


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TABLE OF CONTENTS

# Introduction

The use of color as an information code has been the subject of extensive research. However, opinion is still divided as to how effective it is in assisting an air crewmember to process information. Color cathode ray tube (CRT) displays have made their debut into the commercial aviation cockpit, such as in the Boeing 757, 767 and the Airbus A310, and they have met with subjective pilot approval. Military aircraft that have used color CRTs are the F-14, A-7, F-18, ALPHA-JET, E-6A, P3, F-15 and the Tornado aircraft.

This literature search was conducted to evaluate recent research efforts and results related to the use of color CRTs in aircraft cockpits. The report contains an annotated bibliography of the publications reviewed. Following the bibliography is a summary of the viewpoints found in this literature search and some conclusions that are based on the search and standard human engineering principles.

## Annotated Bibliography

Aretz, A. J., & Calhoun, G. L. (1982). Computer generated pictorial stores management displays for fighter aircraft. Proceedings of the Human Factors Society Twenty-Sixth Annual Meeting, 455-459.

The feasibility of using pictorial and color coded formats to present the pilot with information regarding the stores being carried by the aircraft (stores management information) was investigated. The information was presented via two CRTs in a cockpit simulator of A-7 geometry. Four presentation formats were evaluated: 1) alphanumeric, 2) color pictorial, 3) black and white pictorial and 4) alphanumeric and color pictorial combined. Performance was measured by means of comparing response times taken to answer eight types of stores management questions presented during each mission using the various presentation formats. The results indicated no significant performance differences between the color pictorial, alphanumeric and color pictorial/alphanumeric display formats. However, there was a significant performance difference between these three formats and the black and white pictorial format with response times for the latter being significantly slower. Subjective data collected after completion of the flight tasks indicated that pilots preferred the color alphanumeric/pictorial displays.

Banbury, J. R. (1984). Electronic displays for use in military cockpits. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. I.1-I.19). Farnborough, England: Royal Aircraft Establishment.

The author discusses technical aspects of the trade-offs between color and monochrome head-down CRTs. Various display technologies are considered and the feasibility of using these technologies in civilian and military aircraft is discussed. It is noted that although color CRTs are aesthetically more pleasing and present advantages for coding and cueing in complex displays, several performance penalties have been associated with the use of color CRTs relative to monochrome displays. These penalties include reduced efficiency, lower resolution, reduced vibration tolerance, magnetic field susceptibility, larger physical size and maintenance of color purity. Current technologies and future display possibilities that could help solve these problems are discussed.

Berggrund, U., Derefeldt, G., Hedin, C. E., & Marmolin, H. (1984). Colour coded vs monochrome situational maps. In C. P. Gibson (Ed), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays, (pp. II.1-II.10). Farnborough, England: Royal Aircraft Establishment.

The authors describe an experiment which examined the effects of color coding on search times using situational map displays. Three types of coding were compared: monochrome form-coded targets, color-coded targets and form- and color-coded targets. Symbol size and display density were manipulated for each type of code. Performance was measured for target identification, target location and target counting tasks. Preliminary results indicated statistically significant effects of code type, symbol size and display density.

Boot, A. (1984). Shadow mask CRT visibility problems in an exposed combat cockpit environment. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 12.1-12.9). Farnborough, England: Royal Aircraft Establishment.

The author points out that military applications of shadow mask CRT displays present substantial viewability problems compared to civil cockpit applications. The major problems lie at either extreme of the illumination spectrum. At high ambient illumination levels, the possibility of display wash-out exists due to a lack of display contrast. At low ambient illumination levels, interference with the observer's dark adaptation may present a problem. The author discusses these problem areas in an attempt to identify performance parameters and application techniques that may result in acceptable performance levels.

Brindle, J. H., & Mulley, W. G. (1984). The pursuit of color from a display technology perspective. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 4.1-4.17). Farnborough, England: Royal Aircraft Establishment.

This article states the pros and cons for color CRT use, but notes that the shadow mask CRT is the only available technology for aircraft color video displays. The various display technologies are described and discussed.

Carter, R. C. (1982). Search time with a color display: Analysis of distribution functions. Human Factors, 24(2), 203-212.

The primary purpose of the research described in this article was to aid in understanding and predicting human search times for targets on color displays. The results indicated that response times are best when the target-background color difference is large.

Cavonius, C. R., & Mollon, J. D. (1984). Reaction time as a measure of the discriminability of large colour differences. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays, (pp. 17.1-17.10). Farnborough, England: Royal Aircraft Establishment.

An experiment is described in which discriminability between colors lying along straight lines in CIE-u'v' color space is measured by recording the length of time it took observers to classify two simultaneously presented colors as being the same or different. Discriminability is described as an inverse function of reaction time such that increased response latencies represent a decrease in color discriminability. The results indicated that greater separation between colors along the CIE lines did not produce shorter reaction times, suggesting that conventional representations of color space may overestimate color discriminability. The authors suggest that this be taken into consideration when choosing colors for color coding applications.

DeCorte, W. (1985). High contrast sets of colours for colour CRTs under various conditions of illumination. Displays, 6(2), 95-100.

The author notes that one of the more consistent findings in research comparing monochromatic and color displays is a user preference for color displays. The specific colors chosen for use on displays should, therefore, be perceived as pleasant by the display operators. It is pointed out, however, that the calculation of high contrast sets of colors may generate colors that differ largely in luminosity. In addition, problems related to visual accommodation may result due to chromatic aberrations in the eye. Consideration should also be given to the legibility of colored characters and the identifiability of isolated colors.

Derefeldt, G., Berggrund, U., Hedin, C. E., & Marmolin, H. (1984). Search time: Colour coding and symbol size. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 33.1-33.8).

An experiment is described which tested the effects of symbol size, number of colors and display density on visual search time. The results indicated statistically significant main effects of all three variables. There was a rapid decrease in search time as symbol size increased from four to seven degrees, an increase in search time as display density increased, and a decrease in search time as the number of colors increased from two to ten.

Godfrey, G. W. (1982). Principles of display illumination techniques for aerospace vehicle crew stations (2nd ed.). Tampa, FL: Aerospace Lighting Institute.

The author concludes that color CRTs can be very beneficial in the crew station if applied with good judgment, balancing the benefits and economics. Many tasks will be served just as well with monochrome CRTs as with chromatic displays. For more complex tasks requiring color, sound human factors principles should be adhered to in designing color CRTs into the crew station. Some of the guidelines for incorporating the use of color displays are discussed.

Goillau, P. J., & Home, R. (1984). Colour, luminance, and dark adaptation revisited. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 19.1-19.15). Farnborough, England: Royal Aircraft Establishment.

The study reported here investigated the display spectral characteristics needed for optimum dark adaptation recovery. Subjects were first dark adapted, then viewed a colored field of standard luminance for three minutes (light adaptation), and were then presented with a square wave grating. Reductions in perceptual threshold to the test grating over time were recorded for eight adapting fields of various wavelengths. The results indicated that the amount of time required to achieve dark adaptation recovery was reduced as the wavelength of the light adapting field shifted from 400 to 600 nanometers. There were no differences for light adapting wavelengths exceeding 600 nanometers. The author suggests that in order to achieve optimum dark adaptation recovery, visual displays that are to be used at night should be 10-100 $cd/m^2$ in luminance and should predominantly contain wavelengths above 600 nanometers.

Hudson, P. T. W. (1984). Encoding information in displays: Colour versus non-coloured methods and their uses, or, what can you do extra with a colour display? In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 34.1-34.13). Farnborough, England: Royal Aircraft Establishment.

The author discusses the relations between information on a display and the mental representations of a task formed by the observer. A formal model of display and task-oriented distinctions is presented, and then the utility of color as an encoding mechanism is discussed in relation to this model. It is concluded that color provides a useful way of distinguishing multi-valued categories with more than two types of members, but when only two task distinctions need to be made, other coding formats will serve equally as well.

Jacobsen, A. R., & Neri, D. F. (1985). The effect of set size on color recognition (Report No. 1042). Groton, CT: Naval Submarine Medical Research Laboratory.

A study was performed to determine what effect the set size of a group of colors has on the time required to recognize whether or not a target color belongs to the set. It was found that color is less affected by set size than other coding systems. The authors conclude that the use of color in CRT displays is a step forward in improving the performance of many different tasks.

Jauer, R. A., & Quinn, T. J. (1982). Pictorial formats (Report No. AFWAL-TR-81-3156, Vol. I). Wright Patterson Air Force Base, OH: Air Force Wright Aeronautical Laboratory.

The use of pictorial formats (as opposed to alphanumeric) for displaying six fighter crew station functions is examined. Three modes of pictorial format presentation were compared: monochrome stroke, color stroke and color raster. The results indicated that the color raster format was the most aesthetically pleasing. The authors conclude that although pictorial formats should include a limited amount of alphanumerics for added precision, the use of color facilitates information transfer when pilots must distinguish between classes of stimuli.

Krebs, M. J., Wolf, G. D., & Sandvig, J. H. (1978). Color display design guide (Report No. ONR-CR213-136-2F). Arlington, VA: Office of Naval Research.

This document is an attempt to express concepts and principles in the effective application of color to a display. It deals with generic color displays and specific application to aircraft cockpit use. Particular reference is made to the use of color CRTs in Navy aircraft such as the F-14, A-7, F-18 and VFA-STOL/VTOL.

Several advantages are discussed regarding the use of color CRTs including reduced search times, the ability to use color to visually group information and improved symbol detectability afforded by color. The authors caution that the use of too many irrelevant colors can create "noise" on a display and that similar colors may distract a crewmember. The document was written as a guide for the design and optimum applications of color CRTs.

Luder, C. B., & Barber, P. J. (1984). Redundant color coding on airborne CRT displays. Human Factors, 26(1), 19-32.

The effects of redundant color and shape coding were examined for both an identification and search task under a dual-task paradigm. Compensatory tracking served as the primary task while the secondary task involved making judgements about the state of components on a systems-management display. The presence of redundant color coding on the secondary task resulted in superior tracking performance compared to the condition which used shape coding only. Regarding the response-time data on the secondary task, redundant color coding resulted in improved search performance, but did not prove beneficial for the identification task. The influence of other variables (e.g., display size or number of elements in the display, and inspection load or number of display elements whose state is in question) on performance suggested that shape coding was being processed in a relatively slow, serial manner whereas color coding was being processed in a faster, parallel manner. The authors conclude that color provides spatial economy. The implications of the results on design issues of color CRTs in the cockpit are discussed.

Martin, K. W. (1984). Display visual performance prediction in a military cockpit environment. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 7.1-7.15). Farnborough, England: Royal Aircraft Establishment.

The major focus of this paper is that there is much subjective evidence that color CRTs in the cockpit are better than monochromatic ones, but there is little objective data to support this. Objective performance predictions are very difficult to achieve. It is concluded that color improves the data transfer rate on complex CRT formats. It is also concluded, however, that aesthetic overindulgence can easily enter into the format design and should be avoided.

McGlade, D., & Jordan, D. R. (1984). Digitally generated maps and their implications for cockpit design. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 8.1-8.7). Farnborough, England: Royal Aircraft Establishment.

This paper concentrates on one specific application of maps, namely a display in an aircraft cockpit for use by a pilot. It is concluded that full color is absolutely essential for digital map displays.

Narborough-Hall, C. S. (1985). Recommendations for applying colour coding to air traffic control displays. Displays, 6(3), 131-137.

This article primarily addresses the use of color on air traffic control displays. However, the advantages and disadvantages that are discussed contain information that is valid for considering the use of color in the cockpit as well. One such advantage is that color can prove beneficial for separating and distinguishing different classes of information. However, the allocation of color codes should be done carefully based on an analysis of the types of information needed by the operator and how the information is to be used. The author cautions that illogical uses of color will degrade performance. Another advantage of color coding is a reduction in the operator's visual search time, providing he has prior knowledge of what color to search for. It is also suggested that color coding may help to reduce the number of operator errors and that color may prove especially beneficial when used redundantly with some other type of coding element, such as shape. For complex displays of brief exposure, color coding may also enhance the operator's memory for such tasks as item location.

Some potential disadvantages of color coding are also discussed. Due to chromatic aberrations of the eye, color coded information of different colors may appear at different visual distances. This will be most pronounced for pure colors. In addition, chromatic induction may occur in which the perception of color is changed by the influence of adjacent colors in the operator's field of view. Another potential disadvantage is that information coded by the same color may be interpreted as more similar than it actually is making distinctions more difficult. Conversely, information coded by different colors may be perceived as more different than it actually is, thereby inhibiting comparisons across colors. Finally, the author notes that 8 percent of males and 0.4 percent of females are color defective.

Reising, J. M., & Calhoun, G. L. (1982). Color display formats in the cockpit: Who needs them? Proceedings of the Human Factors Society Twenty-Sixth Annual Meeting, 446-449.

The use of color coding for flight displays using computer generated imagery (CGI) is discussed. Guidelines as to when color coding will or will not improve performance are also discussed. The authors also address the idea of expanding the kinds of color codes currently used to include three types of coding: 1) single purpose color coding (e.g., red for enemy aircraft, amber for unknowns, and green for friendlies), 2) color as part of the environment (e.g., blue for sky and brown for mountainous areas), and 3) dual purpose coding which combines single purpose codes with color as part of the environment. Some of the conclusions reached by the authors are that subjective data show a strong pilot preference for color displays and that color displays will be needed in future cockpits because the displays will be very complex and dynamic. It is suggested that evaluations of color CGI formats should include the collection of both objective and subjective data since objective data alone may not always indicate performance improvements associated with the use of color coding even though there is a strong pilot preference for color.

Reising, J. M., Emerson, T. J., & Aretz, A. J (1984). Computer generated formats for advanced fighter cockpits. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 31.1-31.9). Farnborough, England: Royal Aircraft Establishment.

The authors discuss the role of the pilot in advanced avionics systems and how pictorial display formats using color will benefit the missions of the 1990s and beyond. The future role of the pilot is described as system manager rather than controller or subsystem monitor due to increasing levels of automation. Distinctions are also made between three types of human decision making: skill-based, rule-based and knowledge-based. It is argued that although humans can perform at each level of decision making, optimum performance occurs at the rule-based level. Therefore, advanced avionics systems should be designed to place the pilot in a rule-based decision making role. The use of color pictorial displays is suggested as a means by which this goal can be obtained.

Robertson, P. J., & Jones, M. R. (1984). Subjective reactions to misconvergence on a colour display. Displays, 5(3), 165-169.

Subjective ratings of various degrees of misconvergence were obtained from subjects viewing text and graphics pictures on a shadow mask color CRT display. The results indicated that the subjective quality of a color display decreases as misconvergence increases above 0.2mm.

Santucci, G., Menu, J. P., & Amalberti, R. (1984). Single or multicolor displays: How to choose. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 24.1-24.13). Farnborough, England: Royal Aircraft Establishment.

The authors point out that color may be perceived incorrectly, depending on luminosity and the operator's unconscious stereotyping of color.

Silverstein, L. D., & Merrifield, R. M. (1981). Color selection and verification testing for airborne color CRT displays. In Proceedings of the Fifth Advanced Aircrew Display Symposium (pp. 39-81). Patuxent River, MD: Naval Air Test Center.

The authors describe the human factors and display hardware considerations which impact the selection of colors for modern airborne color CRT displays. The advantage that color allows for more integrated and efficient methods of presenting information is discussed. The authors also discuss the problems of display visibility and color perception due to dynamically changing ambient illumination levels experienced in military aviation environments.

Silverstein, L. D., & Merrifield, R. M. (1985). The development and evaluation of color display systems for airborne applications, phase I: Fundamental visual, perceptual, and display system considerations (Report No. DOT/FAA/PM-85/19). Patuxent River, MD: Naval Air Test Center.

Objectives of the study were to review current philosophy and standards regarding airborne applications of color CRTs, develop guidelines for specifying and measuring color CRT performance, evaluate currently available systems, and predict future trends in color CRT applications. Regarding the advantages of color coding, the authors discuss the aesthetic benefits of color, reduced visual search times and increased symbol visibility. It is also pointed out, however, that an understanding of the complex interface between observer and display is incomplete.

Simon, B. (1984). Aircraft manufacturer experience in color displays integration. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 38.1-38.13). Farnborough, England: Royal Aircraft Establishment.

Two series of flight tests performed on a Dassault ALPHA-JET aircraft equipped with a shadow mask CRT are described. The flight tests were performed to identify problems associated with the use of color displays. The results indicated that it is technically possible to use color CRTs in the military cockpit environment. The author notes that consideration must be given to better brightness control in both stroke and raster modes, filter quality and efficiency, and the operational choice of colors.

Taylor, R. M. (1985). Colour design in aviation cartography. Displays, 6(4), 187-201.

A historical review of the use of color in maps is presented. The author concludes that the use of color coding in aviation maps is essential if the information is to be communicated effectively. Principles and guidelines for the use of colors in aviation map displays are discussed.

Wagner, D. W. (1984). The effect of colored symbol aspect ratio on operator performance. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 30.1-30.7). Farnborough, England: Royal Aircraft Establishment.

The author describes a study which examined the effects of symbol ratio (defined as the width-to-length ratio of a line) and symbol area (square minutes of arc measured at the eye) on color discrimination performance. Results indicated that only the symbol area factor significantly affected performance. Performance decrements occurred when the total symbol area was less than nine square minutes of arc.

Walraven, J. (1984). Perceptual artifacts that may interfere with colour coding on visual displays. In C. P. Gibson (Ed.), Proceedings of the Workshop on Colour Coded vs Monochromatic Electronic Displays (pp. 13.1-13.10). Farnborough, England: Royal Aircraft Establishment.

Perceptual artifacts of human color vision are described in an attempt to familiarize the display designer with these phenomena such that potential problems associated with the perception of color displays can be avoided. The following perceptual artifacts are discussed.

- peripheral color vision
- Helmholtz-Kohlrausch effect
- chromatic induction
- assimilation
- McCollough effect
- fluttering hearts effect
- chromatic aberration
- color stereoscopy

For explanations of these phenomena, the article should be consulted.

Ward, F., & Wilson, D. (1984). Development of color criteria for advanced displays (Report No. AFAMRL-TR-84-023). Wright Patterson Air Force Base, OH: Air Force Aeromedical Research Laboratory.

The study reported here describes the development of a methodology for calibrating a color CRT, the results of a color discrimination study, and the development of a strategy for color coding synthetic aperture radar imagery. Results indicated that color discrimination is poorest for red colors, and that black and white coding is superior to color coding.

Way, T. C., Hornsby, M. E., Gilmour, J. D., Edwards, R. E., & Hobbs, R. E. (1984). Pictorial format display evaluation (Report No. AFWAL-TR-84-3036). Wright Patterson Air Force Base, OH: Air Force Wright Aeronautical Laboratories.

The results of two sequential simulation studies are reported. The basic study (study 1) collected both objective and subjective pilot data to evaluate the feasibility of pictorial format displays for presenting flight information for seven basic types of flight displays. The second study used the same basic displays but concentrated on threat warning information presented to the pilots. In both studies, performance and subjective evaluations were compared for both monochromatic and color pictorial formats. Pilots rated the pictorial formats as quite acceptable and preferred color over the monochromatic versions of the displays. Performance was also slightly better using the color versions of the pictorial formats.

Witt, N. W. & Strongman, E. (1983). Application and experience of colour CRT flight deck displays. Displays, 4(2), 77-82.

The authors summarize research comparing monochrome and color electronic flight deck displays carried out by the Civil Avionics Research Section of the Royal Aircraft Establishment (RAE), Bedford. The work was funded by the United Kingdom Department of Industry and performed aboard the RAE BAC 1-11 research aircraft. Based on the research results and the opinions of pilots working with the displays, the authors conclude that color can reduce visual clutter by providing additional information for coding and that color reduces workload associated with information extraction. One potential disadvantage is the presence of flicker between 8-15 Hz. It is suggested that cyan, white and green are the most viable colors for aircraft CRTs.

## Guidelines for Color Coding

The data which are described briefly in the Annotated Bibliography were analyzed in detail and evaluated from the standpoint of usage in aircraft cockpits. The guidelines which follow are presented within the context of the following categories:

- Contrast
- Saturation
- Color for Coding

- Number of Colors
- Color Types
- Background
- Color Distribution
- Task Combinations
- Caution and Warning
- Application
- Cockpit Environment

Contrast

One of the most important factors in the successful use of color CRTs is adequate contrast with the background. Contrast ratios should be within the range of 6:1 to 10:1. Based on current technology the contrast ratio is achievable. An automatic brightness/contrast compensation system is a must for the dynamic ambient lighting environment that will be experienced in the aviation environment.

During the development of the Boeing 757/767 a study concluded that three types of brightness/contrast controls were required:

a. Manual brightness control to accommodate individual differences in the visual sensitivity of pilots as well as the use of sunglasses.
b. Automatic brightness compensation that changes the display luminance as a function of changing ambient light levels incident on the display.
c. Automatic contrast compensation that changes the display symbol-to-background contrast as a function of changing luminance levels in the pilot's field of view.

This type of brightness/contrast control would take into account the fact that observers' contrast sensitivity changes. For example, a pilot's contrast sensitivity increases as background luminance increases. Relatively high contrast is required at low levels of display background luminance, while relatively low contrast is required at high levels of background luminance. When an automatic brightness/contrast control system is not implemented, the operator may tend to drive displays to a higher luminance than required.

The following is a summary of luminance and contrast requirements (see Krebs, Wolf, & Sandvig, 1978).

a. SYMBOL LUMINANCE
   - Minimum for good color perception: 3 $cd/m^2$
   - Optimum under moderate lighting conditions: ranges from 30 to 300 $cd/m^2$

b. BACKGROUND LUMINANCE
   - Visibility of color symbols better on dark background

c. CONTRAST
   - Symbol-to-background luminance ratios of about 6:1 to 10:1

d. AMBIENT ILLUMINATION

- The higher the ambient illumination, the higher the symbol luminance must be to achieve adequate contrast

Saturation

Highly saturated colors have little benefit and can introduce problems. Color adaptation may occur after prolonged viewing of a display with saturated colors. Afterimages may occur after looking away from the screen, which is an undesirable effect, particularly in an aircraft cockpit.

Saturated blues and reds, in particular, fail to satisfy the requirement for adequate contrast as recommended previously. Saturation is a perceptual correlate of purity and is usually taken on the reciprocal of least colorimetric purity; that is, the lower the colorimetric purity, the higher the apparent saturation of the spectral light.

Color for coding

Color is a very dominant coding device. Therefore, ambiguities and errors will result if the same colors are used to draw different distinctions within any system. For example, the conventional significance of the color red is that of warning or danger. If it is used for that purpose, it should not be used for others.

Based on data derived from the Boeing 757/767 program, it is recommended that color not be used as a singular information code. On the 757/767 flight displays, color is always combined with shape or positional coding of symbology to produce a highly reliable, partially redundant form of information coding.

An experiment by Luder and Barber (1984) suggests that when the task is that of searching the display, substantial gains can be expected from redundant coding. For example, on a radar or tactical navigation display, color could be used to supplement the shape coding used to distinguish between hostile, friendly and unknown aircraft.

Existing literature further suggests that color will be particularly useful in high-density displays, so long as colored targets are not so small as to preclude color discrimination.

Number of colors

The number of colors should be limited to those that will actually help the operator, as irrelevant colors can be confusing. Most authors recommend between three to six colors. This number may be exceeded for maps.

In contexts where relative judgments are required and where color is used with other coding dimensions, a fairly large number of colors may be advantageous.

Research data reviewed in Krebs, Wolf, and Sandvig (1978) recommend no more than four colors on a display. It was determined that human observers can identify up to 50 colors. However, if more than 10 colors are presented at the same time, identification errors increase significantly.

Color types

Perceptually, the most usable colors appear to be relatively unsaturated yellows, greens, magentas, cyans and oranges that can be readily distinguishable from each other and meet contrast requirements, and can be satisfactorily used in conjunction with white. A lightly saturated blue is regarded as a poor choice for detailed information. Two colors that are not easily discriminable should not be chosen for use on one display. For example, yellow can be easily confused with orange and green.

In addition to the perceptual aspect of color types to be used are the human factors requirements which need to be considered.

The following recommended display colors are based on the study described in Krebs, Wolf, and Sandvig (1978). They are recommended for the dynamically changing ambient light conditions experienced aboard military aircraft.

Recommended display colors (see Krebs, Wolf, & Sandvig, 1978)

- GREEN - Recommended as the predominant color for coding except for the classes of information specified below.

- YELLOW - Best suited for moderate priority or cautionary information.

- RED - Recommended for high priority information, particularly to indicate threat or danger situations.

- BLUE - Use to perceptually separate related or adjacent symbology. Should not be used redundantly with shape coding since blue generally reduces legibility.

- DESATURATED ORANGE - May be used in place of green for coding sensor imagery or computer-generated map imagery.

- DESATURATED GREEN - May serve as an alternative to desaturated orange for coding sensor imagery.

Alternative color recommendations (see Krebs, Wolf, & Sandvig, 1978)

One relatively simple coding scheme is a three-color system consisting of green, yellow and red. Such a system provides adequate separation in color space for easy discrimination. The use of three colors also provides the minimum number of colors necessary for coding information according to priority. This type of coding system may be well suited for situations in which pilot workload is not excessive.

For situations imposing higher degrees of workload where more efficient information transfer is desirable, a more complex coding system may be necessary. Such a system might consist of green, yellow and red plus one or more of the other colors recommended in the previous section. The number of colors and the coding assignments chosen will be determined by functional requirements and system limitations.

Background

A dark background provides for high contrast. However, a black background may be excessive and characters may seem to float in space. A very light background may not provide sufficient contrast in high-ambient light. It is better to have a greyish background that remains neutral under ambient illumination.

The display background should be chosen not only in relation to the colors of the characters, but also in relation to the ambient lighting and the brightness of other cockpit displays. It is also possible to use data characters against a colored background, although this may involve thickening the characters to retain their legibility. If background coloring is used extensively, the display will have a greater light output than other displays in the environment. This can induce changes in pupil size whenever the viewer looks from one display to another. Research suggests that this may be a common source of reported fatigue.

Color distribution

For tasks requiring visual search, it is generally recommended that the number of targets in any one color should not exceed 50 percent of the total number of targets on the display. It is recognized, however, that such a restriction may not be possible to achieve in military operational environments.

Task combinations

Tasks generally do not deal with simple categories, such as search and identification, but a combination of different tasks. Hence, when choosing colors it is vital to consider all the tasks that have to be performed. The optimum balance of the advantage of color coding across all tasks should be ensured while minimizing any unwanted sources of error for specific tasks.

Caution and warning

Color is not necessarily always an effective attention cue unless it is coupled with another coding mechanism (e.g., audible tones). Red may well be an exception since it represents an already well-learned association. Color coding may especially be enhanced when used redundantly with shape coding.

Application of color

Color application must be carefully considered before altering any color because the strong associations already learned may be extremely difficult to change. For instance, the color red has been used to indicate a warning and has become associated with danger by pilots. It would be extremely detrimental at this time to say, for example, that blue is now the color for warnings. During the relearning process many errors would be made by crews that confused red and blue applications.

Cockpit environment

Cockpits of most Army aircraft are surrounded by transparencies in front, on both sides, and the top. Ambient lighting in a cockpit of this type is expected to reach about 107,600 $lm/m^2$. When illuminated by an overhead sun, the background luminance of a virtual image display can exceed 34,000 $cd/m^2$. Displayed information must remain legible under such extreme ambient conditions.

On the other hand, flying at night often requires maximum visual dark adaptation on the part of the pilot to facilitate target detection and obstacle avoidance. Under these situations, a display luminance of less than 3.5 $cd/m^2$ is required to preserve dark adaptation. An automatic contrast/brightness adjust system is a must for cockpit displays.

## Conclusions

A review of the documents cited in this literature search has yielded some advantages and disadvantages of using color CRTs in aircraft cockpits. It is believed, however, that with the advancement of color display technology and with proper design and application, the use of color on aircraft CRTs will prove beneficial. In addition to general pilot acceptance, color CRTs provide the capability of improving symbol definition allowing for the presentation of more information on the screen. Colored mapping displays have significantly reduced pilot workload and are probably the most efficient utilization of color CRTs. Bearing in mind that color electronic displays look ready to rival monochrome displays in areas such as cost, weight and reliability, it is hard to imagine that they will fail to become an essential component of the cockpit. The following is a list summarizing the advantages and potential disadvantages of the use of color CRTs in the cockpit.

Advantages

Color is a code just as shape and size are codes. Color will be helpful if (1) the display is unformatted, (2) symbol density is high, (3) the operator must search for information, (4) symbol legibility is degraded and (5) the color code is logically related to the pilot's task. The following paragraphs will discuss some of the advantages of using color.

Reduced search time

There is little objective data to verify that there is performance improvement due to color CRTs. However, in the case of search time, data show that it can be reduced by 70 percent when using color (see Luder & Barber, 1984; Krebs, Wolf, & Sandvig, 1978).

Reduced workload in extracting information

A study using a BAC-1-11 research aircraft concludes that color systems substantially reduced workload in extracting information from the display (see Witt & Strongman, 1983). Reduced search time is the main factor in this conclusion.

Pilot preference

The results of several studies show that there is widespread pilot preference for color displays (see Aretz & Calhoun, 1982; Reising & Calhoun, 1982). In addition to the data in the literature, when several pilots (commercial and military) were asked about their preference of color vs. monochromatic displays, all preferred color. Their reasons were mainly decreased search time and improved legibility of mapping displays.

Future need due to more complex displays

Several studies conclude that color displays will be needed in the future cockpit because the displays will become more complex and dynamic, and may consist of degraded symbology (see Reising & Calhoun, 1982). Through very careful blending of color codes within the test of a display format, it should be possible to provide a simple, clear information presentation to the aircrew that will aid them in completing the increasingly demanding missions.

Full color maps are essential

One of the best applications of color CRTs is mapping displays (see McGlade & Jordan, 1984). Human factors research shows that the usefulness of color coding in information displays tends to increase with information density and complexity. Maps are one of the most complex forms of information displays and it is, therefore, not surprising that cartography is often influenced by historical facts and conventions that have little relevance to computer generated electronic displays. It appears clear from a variety of practical experiences and empirical studies that maps, more than any other kind of information display, need to be colored in order to communicate effectively.

Faster responses and fewer errors

It has been shown that response times in finding targets on displays are improved with color (see Carter, 1982; Aretz & Calhoun, 1982; Krebs, Wolf, & Sandvig, 1978; Martin, 1984).

Increased symbol visibility

Color provides for increased symbol visibility and detectability (see Krebs, Wolf, & Sandvig, 1978).

Performance improvement

There are several studies that indicate there is some improvement in overall pilot performance when using color (see Aretz & Calhoun, 1982; Jacobsen & Weri, 1985; Way, Hornsby, Gilmour, Edwards, & Hobbs, 1984).

Error reduction

Some data are available which show that there is a reduction in errors with color symbols vs. achromatic symbols on displays (see Wagner, 1984).

Disadvantages

The following paragraphs describe some of the major disadvantages that were pointed out in the literature that was reviewed.

Improper use of colors

Too many colors can be detrimental, especially when they are similar. Too many irrelevant colors in a display can become "noise" (see Krebs, Wolf, & Sandvig, 1978). This should not be considered as a color disadvantage, but a possible misuse of color.

Color CRT power usage

Color CRTs require more power, produce more heat and have reduced vibration tolerance (see Banbury, 1984). It is expected that these disadvantages will be eliminated as the color display technology advances.

Little objective data

There appears to be more objective, scientific data to support color disadvantages than advantages (see Reising & Calhoun, 1982; Martin, 1984).

Aesthetic overindulgence

One of the drawbacks of designing color CRTs is the fact that frequently, aesthetics are preferred over useful performance data (see Martin, 1984).

Display washout and night vision

It has been shown that high ambient illumination causes display washout, while low ambient illumination (night) causes night vision adaptation problems (see Boot, 1984). Automatic contrast adjustment might solve this problem.

Detrimental perceptual phenomena

There are a number of perceptual phenomena that can interfere with normal, predicted perception of colors (see Walraven, 1984). These phenomena are difficult to predict and may lead to errors by the crew.

Misconvergence

Misconvergence of the primary colors in a shadow mask CRT is one of its disadvantages relative to monochrome displays. It was found that the subjective quality of a color display reduces significantly as misconvergence increases above about 0.2 mm or 25 percent of spot width. Areas of greater misconvergence are tolerable if small, however. For this type of display, in order to satisfy the users' subjective requirements, the misconvergence should be not more than 0.3 mm or 38 percent of spot width and should typically be not more than approximately 0.2 mm or 25 percent of spot width (see Robertson & Jones, 1984).

Red-Green deficiency

Eight percent of the U.S. male population and 0.4 percent of the U.S. female population has a red-green deficiency (see Narborough-Hall, 1985).

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